An Introduction to Marine Controlled Source Electromagnetic Methods

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ABSTRACT

Early development of marine electromagnetic methods, dating back about 80 years, was driven largely by defense/military applications, and use for these purposes continues to this day. Deepwater electric dipole–dipole controlled source electromagnetic (CSEM) methods arose from academic studies of the oceanic lithosphere in the 1980’s, and although the hydrocarbon exploration industry was aware of this work, the shallow water environments being explored at that time were not ideally suitable for its use. Low oil prices and increasingly successful results from 3D seismic methods further discouraged investment in costly alternative geophysical data streams. This changed in the late 1990’s, when both Statoil and ExxonMobil began modeling studies and field trials of CSEM surveying in deep water (around 1,000 m or deeper), specifically for characterizing the resistivity of previously identified drilling targets. Trials offshore Angola in 2000–2002 by both these companies showed that CSEM data can successfully be used to evaluate reservoir resistivity for targets up to several thousand meters deep. Both companies levered instrumentation and expertise from the academic community in order to make rapid progress. Although industry is still to some extent catching up with academic expertise in CSEM methods, at the time of writing marine CSEM data is an industrial commodity within the exploration business, with services offered by three companies. The ability to determine the resistivity of deep drilling targets from the seafloor may well make marine CSEM the most important geophysical technique to emerge since 3D reflection seismology.

Introduction

Marine controlled-source electromagnetic (CSEM) surveying has been transformed recently from a relatively obscure academic discipline to a promising new tool for remotely detecting and mapping offshore hydrocarbon reservoirs. This transformation has been driven in large part by the technical and economic challenges associated with exploration in the deepwater environment. For example, seismic hydrocarbon indicators lack perfection, and deepwater exploration wells are sufficiently expensive that it make sense to collect additional data sets if these add information which can provide new insights and significantly reduce risk. Early indications are that marine CSEM may provide some risk reduction in this regard, and at the time of writing, the industry is attempting to assess this apparently new technology. It is fair to say that oil and gas companies and the national licensing entities hold views on marine CSEM varying from cautious observation, judicious use, though to enthusiastic embrace. In this paper we review some of the history of the method and present some early examples of the technology in use.

Figure 1 introduces the basic method we will discuss. A horizontal electric field transmitter is towed close...
to the seafloor to maximize the energy that couples to seafloor rocks. A series of seafloor multicomponent electromagnetic receivers spaced at various ranges from the transmitter record the amplitude and phase of the transmitted signal as a function of source–receiver offset and frequency (which is between about 0.1 and 10 Hz). Since the electromagnetic skin depth is almost always smaller in seawater than in sub-seafloor rocks, at sufficient source–receiver offset the electric and magnetic fields measured by the receiver instruments have travelled almost entirely beneath the seafloor. This phenomenon breaks down in shallow water and at low frequencies, where the air layer exerts a significant, sometimes dominant, influence. Since they are equipped with magnetic as well as electric sensors, the receivers also record magnetotelluric (MT) signals that arise from natural fluctuations in Earth’s magnetic field. The MT signals can be viewed either as a source of noise for CSEM or a useful technique for recovering geological structure.

Figure 1. Schematic representation of the marine CSEM method. See text.

Motivation

In geophysics, electrical and electromagnetic (EM) methods are used to measure the electrical properties of geological formations. At the low frequencies used in marine CSEM, the rock resistivity accounts for almost all of the electromagnetic response. Since replacement of saline pore fluids by hydrocarbons (gas, gas condensate, or oil) increases the resistivity of reservoir rocks, EM methods are clearly important exploration tools, but until recently the main application of electrical methods in the oil and gas business has been well logging. The MT method has been used on land since the 1950’s (Vozoff, 1972), and since the 1980’s in the marine environment (Key et al., 2006), to image geological structure as part of the exploration
process. The MT method is particularly useful for mapping geological features such as salt, volcanics, and carbonates that present challenges to the seismic methods. However, because MT currents within the earth are generated mostly in the horizontal plane, thin sub-horizontal resistive formations are almost invisible to the MT method, and so the technique alone is not useful for hydrocarbon fluid detection. The dipole transmitters used in marine CSEM, on the other hand, generate vertical electric fields that sense horizontal resistors of sufficient size.

**Historical context**

**Beginnings**

The use of electromagnetic methods in hydrocarbon exploration dates back to the beginning of the 20th century (e.g. Rust, 1938), and on land continues to this day, mainly through MT surveys carried out to provide structural constraints. Marine electrical methods started with DC resistivity surveys carried out over water within only a few years of the method’s inception (Schlumberger et al., 1934). For DC methods to have any great sensitivity, seafloor resistivity has to be less than seawater resistivity (which is 0.25 to 0.3 $\Omega$m, depending on salinity and temperature), and so the main application was prospecting for sulphide ores. Early work carried out over 80 years ago off the Cornish coast is reviewed by Francis (1985), and much more recently Francis (1977) carried out a Wenner survey in the same area of England. In the context of current marine CSEM practice, it is interesting to note that this early surface-towed array had an emission current of 2000 A provided by the generators of a minesweeper. Wynn (1988) developed a marine induced-polarization system to explore for mineral sands. However, these are all shallow-water systems, and the market for offshore mineral mining is small, so little commercial activity in marine DC methods has developed.

Some of the earliest work on AC marine electromagnetic methods involves military applications, dating back to early in the last century with work on submarine cables and ship guidance (Drysdale, 1924). The use of electric and magnetic fields for vessel detection and characterization continues to the present time, although given the nature of the applications publications are hard to find. The proceedings of the various MARELEC conferences probably provide the best unclassified view of this field.

**Academic development of CSEM**

The deepwater marine CSEM method as used today for hydrocarbon exploration was developed by Charles Cox of Scripps Institution of Oceanography in the late 1970’s (Cox, 1981), with the first experiment being
carried out on a mid-ocean ridge in the Pacific in 1979 (Speiss et al., 1980; Young and Cox, 1981). Cox was already working on seafloor magnetotelluric equipment and methodology (Cox et al., 1971), and the original motivation was to study the shallow and resistive parts of the oceanic lithosphere by replacing the relatively high frequency energy lost to magnetotelluric fields with a deep-towed man-made transmitter. Early funding for instrument development came from the U.S. Defense Advanced Research Projects Agency (DARPA), which was interested in the effect of the seafloor on submarine communications. Support also came from the U.S. Office of Naval Research (ONR), which wanted to learn more about the seafloor noise environment. Several early experiments (e.g. Webb and Constable, 1986) involved combined deployments of a sensitive broadband pressure variometer (known as the differential pressure gauge, or DPG; Cox et al., 1984) and sensitive electric field recorders (Webb et al., 1985). With the funding agencies’ interest in the resistivity structure of ‘normal’ oceanic lithosphere, the next few experiments moved away from the ridges to more representative crust (Cox et al., 1986; Constable and Cox, 1996). The oceanic lithosphere proved to be remarkably resistive; the lower crust and upper mantle exceeds 1 MΩm, and the resistivity–thickness product of the lithosphere exceeds $10^9$ Ωm². Combined with the high conductivity–thickness product of the oceans ($10^4$ S), the effect of such a resistive lithosphere is to trap horizontal electric currents associated with MT fields or horizontal water flow in the ocean for very large distances.

As useful as this information is about the normal seafloor, geological interest then (and now) is biased towards areas of tectonic activity such as the mid-ocean ridges that provided the initial target for CSEM studies. Martin Sinha and his group from the University of Cambridge started to develop a marine CSEM system in the mid-1980’s (Sinha et al., 1990). Their equipment was based largely on the Scripps system, but with one very important improvement: use of a neutrally buoyant transmitter antenna which allowed the deep-towed transmitter to be ‘flown’ about 100 m above the seafloor. This was necessary for working over the very rough terrain of the ridge axis, and proved to be desirable later in the hydrocarbon exploration environment. First trials of the Cambridge system were carried out in 1987 and 1988. This was followed by collaborative Cambridge/Scripps experiments on the East Pacific Rise (Evans et al., 1991), the Reykjanes Ridge (MacGregor et al., 1998), and the Valu Fa Ridge (MacGregor et al., 2001). In late 1998 the Cambridge group moved to Southampton University.

Although the deepwater frequency–domain horizontal electric dipole–dipole system appears to be the most appropriate tool for exploration, other marine CSEM techniques have been tested, notably by Nigel Edwards’ University of Toronto group. Cheesman et al. (1988) deployed a horizontal magnetic dipole–dipole time domain system, and Edwards et al. (1985) tested a variation of his land magnetometric resistivity technique
in the ocean, utilizing a vertical low frequency electric transmitter that hangs from the ship to the seafloor. Both these techniques are being currently used for relatively shallow geophysical surveys (e.g. Evans et al., 2000; Evans and Webb, 2002). Yuan and Edwards (2000) developed a short-offset time domain electric dipole–dipole system for gas hydrate characterization.

Collection of data sets cannot proceed far without supporting theory and numerical modeling algorithms. Early work depended on the asymptotic solutions of Kraichman (1970) and Bannister (1968; 1984). The first widely available layered model solution for the frequency domain electric dipole method was published by Chave and Cox (1982), and some discussion in the literature developed around the issue of quadrature versus digital filtering for the solution of the Hankel transforms involved in the 1D calculations (Anderson, 1984). One dimensional solutions for the time domain methods were produced by the Toronto group (Edwards and Chave, 1986; Cheesman et al., 1987). Flosadottir and Constable (1996) implemented the fast Hankel transform of Anderson (1989) along with the OCCAM inversion algorithm of Constable et al. (1987) into the Chave and Cox algorithm to produce a rapid 1D inversion code. Numerical finite element solutions to the 2D electric dipole problem were developed for the time domain by Everett and Edwards (1993) and for the frequency domain by Unsworth et al. (1993). Unsworth and Oldenburg (1995) demonstrated a subspace inversion method using the frequency domain code, but as far as we know this was never tested on real data. The first 2D inversion of real data was published by MacGregor et al. (2001), who modified the Unsworth forward code to handle experimental geometries and bathymetry and implemented the OCCAM inversion algorithm.

Three dimensional analytic solutions have not been developed for the marine CSEM case per se, but 3D numerical algorithms are generally flexible enough to include a water layer, and sometimes an air layer, as part of the structure, particularly if they have been developed with borehole applications in mind, where the source and receiver are both within the conductive structure. One code that is in extensive use within the marine exploration community is the finite difference algorithm of Newman and Alumbaugh (1995). Badea et al. (2001) describe a 3D finite element algorithm.

Early industry involvement

ExxonMobil (then Exxon) was aware of work being carried out by Scripps and others, and investigated the use of marine EM for exploration in the early 1980’s; a patent was issued in this regard (Srnka, 1986). Following a series of numerical and physical (graphite) model experiments, Exxon scoped a field test using a naval minesweeper (like Francis) and both seafloor and towed electric sensors under development at Scripps.
Scripps held a meeting in April 1984 to generate support for the development of exploration CSEM, which resulted in a small project being funded by Amoco, Arco, Elf, and Sohio. (Current supporters of marine CSEM might note that none of these companies exist today.) The result of this work is reported in Constable et al. (1986) and Chave et al. (1991). However, exploration water depths at that time were around 300 m, and that, coupled with a lack of computational capability, limited digital acquisition capacities, and the growing emphasis on 3D marine seismic technology, meant that this work was far ahead of its time in terms of commercial viability.

This all changed in the late 1990’s. Exploration was by then being routinely carried out in water 1000 m deep, and ExxonMobil resumed and Statoil started examining marine CSEM as a tool for hydrocarbon exploration. One of us (SC) was invited to review Statoil’s internal research project in November 1999, which consisted of a variety of numerical and analog modeling (featuring an innovative use of a water-bed mattress!). The conclusion was that:

“... if the target is not too small compared with its depth of burial, and the water depth is sufficient to suppress the air wave, then the controlled source signature of the oil-filled layer is detectable, yielding controlled source amplitudes that are a factor of 2 to 10 different than models without the oil layer. The signals are above the noise threshold, and the experimental parameters (frequency, range, antenna length, and power) are practicable.”

This was sufficient for Statoil to proceed with field trials offshore Angola in late 2000, described below. Around the same time (research was underway in mid-1998), ExxonMobil was carrying out investigations into the use of 3D EM methods for marine CSEM survey design, acquisition, data processing, inversion, and interpretation. ExxonMobil’s field programs started in late 2001 with field trials off Scotland, followed by West African tests shortly afterwards (examples are also shown below).

It is important to note that exploration’s move to deeper water had already driven interest in marine MT as an exploration tool, which had led to the development of commercially viable CSEM/MT receiver instrumentation. Although early attempts to use the MT method in the marine environment (Hoen and Warner, 1960) foundered for reasons similar to the early CSEM attempts (shallow water, lack of digital equipment, etc.), by the early 1990’s electromagnetic techniques were being considered as an aid to mapping base of salt in the Gulf of Mexico (Hoversten and Unsworth, 1994). In April 1994 a prototype MT receiver based on the Scripps CSEM receiver was deployed off southern California, and the results were sufficiently encouraging to attract support from industry to develop the instrumentation (Constable et al., 1998) and
method (Hoversten et al., 1998). This early work consisted of a collaboration between Mike Hoversten and Frank Morrison of U.C. Berkeley, Arnold Orange of AOA Geophysics, and Scripps. Field trials over the Gulf of Mexico Gemini prospect between 1996 and 2003 resulted in systematic refinement of the instrumentation and methodology (Hoversten et al., 2000; Key et al., 2006). Commercial surveys were carried out by AOA using Scripps equipment in the Mediterranean (1995 and 1996, for Agip), Gulf of Mexico (1998, for Agip and BP), and North Atlantic (2001, for Agip and Statoil).

The Marine CSEM Method

The theory and practice of the marine CSEM method is fairly well documented. In addition to the references cited in the Introduction, we refer the reader to Edwards (2005) and Constable and Weiss (2006). Here we will just summarize the key elements. The frequency domain dipole–dipole electric configuration shown in Figure 1 is the method of choice for various reasons:

a) An alternative to the frequency domain approach is the time domain method, which is well suited to land exploration where the geological formations are on the conductive side of the air/earth system; the direct wave in the atmosphere dissipates at the speed of light after transmitter turn-off to leave eddy currents propagating more slowly in the ground. On the deep seafloor, the seabed is generally more resistive than the seawater, and so information about the geology is embedded in the early time response, while the (uninteresting) seawater response dominates late time. In the frequency domain, however, the longer skin depths associated with seafloor rocks means that at sufficient source–receiver distance the field is dominated by energy propagating through the geological formations. Energy propagating through the seawater has essentially been absorbed and is absent from the signals. Furthermore, by concentrating all the transmitter power into one frequency, larger signal to noise ratios can be achieved at larger source-receiver offsets.

The reader should bear in mind, however, that these are operational considerations, and that the physics of both the time domain and frequency domain methods are the same. In principle, at least, a sufficiently broadband frequency domain survey would be equivalent to a time domain survey.

b) Electric fields are well suited to operation in seawater. Transmitter currents of 1,000 A or more can be passed through seawater with simple electrode systems and reasonable power consumption (of order 100 kW), and easily towed through the seawater along its length. Receiver noise is very low, since cultural and MT noise is highly (if not totally) attenuated in the CSEM frequency band. Magnetic field receivers can, and are, employed, but motion of the sensors associated with water currents moving the receiver instrument
limits the noise floor. (On land, magnetic sensors are buried to avoid this, but can still be subjected to noise associated with ground motion from trees, microseisms, traffic, etc.)

c) A horizontal electric dipole excites both vertical and horizontal current flow in the seabed, maximizing resolution for a variety of structures. A vertical magnetic dipole, for example, would excite mainly horizontal current flow (Chave et al., 1991). Horizontal magnetic dipoles also excite both vertical and horizontal currents, but are less favored than electric dipoles for operational reasons.

With reference to Figure 1, the CSEM transmitter excites energy throughout the seafloor–seawater–atmosphere system. However, since the fields decay both geometrically and (most importantly) exponentially with a characteristic e-folding distance given by skin depth \( z = \sqrt{2\rho/\omega\mu_0} \) where \( \rho \) is resistivity, \( \mu \) is permeability, and \( \omega = 2\pi f \) is angular frequency, the tendency is that for a given source–receiver range propagation through one part of the system will dominate the received fields. This has been illustrated in Figure 2, where we have presented the amplitude and phase curves versus source–receiver offset for the canonical oilfield model (a 100 \( \Omega \)m reservoir 100 m thick buried at a depth of 1,000 m in a host sediment of 1 \( \Omega \)m in 1,000 m water depth). To highlight all the dominant propagation paths in one figure, we have taken a transmission frequency of 10 Hz, which yields signals too small to measure, and made the calculations using the 1D code of Flosadottir and Constable (1996).

**Figure 2.** Radial (solid lines) and azimuthal (broken lines) amplitude and phase responses over the canonical model for a frequency of 10 Hz and a transmitter altitude of 30 m.

The skin depth in water is 87 m, so very close to the transmitter we see the \( 1/\text{range}^3 \) amplitude falloff from a static dipole and nearly constant phase. At ranges between a few hundred meters and 2 km, skin depth in
the seafloor sediment (158 m) is larger than in seawater and we see exponential attenuation dominated by the seafloor resistivity. Up to this point, the mathematics of propagation is reasonably well approximated by the double halfspace (i.e. infinite water depth and no reservoir layer) solution of Chave et al. (1991), valid for very resistive seafloor:

\[
E_\rho = \frac{A\rho_o}{2\pi} \cos \phi \left[ \frac{(\gamma_o r + 1)}{r^3} e^{-\gamma_o r} + \frac{(\gamma_r^2 r^2 + \gamma_r r + 1)}{r^3} e^{-\gamma_r r} \right]
\]

\[
E_\phi = \frac{A\rho_o}{2\pi} \sin \phi \left[ \frac{(\gamma_o r + 1)}{r^3} e^{-\gamma_o r} + \frac{2(\gamma_r r + 1)}{r^3} e^{-\gamma_r r} \right]
\]

\[
\gamma_o = \sqrt{i\omega \mu_o / \rho_o} \quad \gamma_r = \sqrt{i\omega \mu_o / \rho_r}
\]

(\rho_o and \rho_r are seawater and seafloor resistivities respectively). Here \(E_\rho\) is the radial, or in-line, electric field and \(E_\phi\) is the azimuthal, or broadside, electric field, \(r\) is source–receiver offset, and \(A\) is the source dipole moment (transmitter current \(\times\) antenna length). The dipole azimuth is \(\phi\), which would be 0° for the purely radial mode shown in Figure 2 and 90° for the purely azimuthal mode. The \(\gamma\) are complex wavenumbers, related to \(1/\text{(skin depth)}\). The \(r^3\) dipole dependence is evident in these equations, along with terms associated with exponential attenuation through the water (first term, in \(\gamma_o\)) and through the seafloor rocks (the second term, in \(\gamma_r\)).

Referring again to Figure 2, at ranges between 2 km and 10 km we see increased electric field amplitudes associated with a larger skin depth (1600 m) in the more resistive reservoir layer. There is a corresponding increase in apparent phase velocity. Finally, at ranges greater than 10 km propagation through the atmosphere dominates the receiver fields and the amplitude returns to a \(1/r^3\) dipole attenuation, along with a phase that becomes constant (i.e. the apparent phase velocity is now comparable to the speed of light).

Much has been made of the different behavior of the azimuthal and radial modes in the presence of a thin resistor (e.g. Eidsmo et al., 2002; Constable and Weiss, 2006), whereby the azimuthal mode has a very much smaller reservoir response than the radial mode. This is true only at relatively low frequencies where the CSEM fields are dominated by the galvanic response of the reservoir (a charge buildup on the upper and lower surfaces of the resistive layer) generated by the vertical electric fields of the radial mode (which are largely absent in the azimuthal mode). Here, the frequency is high enough that inductive effects in the reservoir layer produce a significant response in the azimuthal mode. The static vertical offset between the
radial and azimuthal modes is presumably associated with the galvanic contribution of the reservoir to the radial mode fields.

**Equipment**

Transmitted electric fields are directly proportional to the source dipole moment $A$, in turn given by the dipole length times the emission current. Dipole lengths are typically 100–300 m; significantly longer and towing them close to the seafloor would become technologically challenging. Current practice is to transmit high voltage AC (typically 400 Hz) current down a towing cable to a transmitter unit close to the seafloor. Although purely AC transformed sources are in use, most systems transform the high voltage to low voltage/high current, rectify this low voltage AC, and switch the resulting quasi-DC into a square wave or other binary/ternary signal (e.g. Sinha et al., 1990; Constable and Cox, 1996). To estimate what magnitude transmission currents can be achieved, we work back from the antenna electrodes. The resistance to seawater is purely a function of seawater resistivity $\rho$ and geometry; for a long cylindrical electrode the resistance per electrode is given by

$$R = \frac{\rho o}{2\pi L} \left[ \ln \left( \frac{2L}{a} \right) - 1 \right]$$

(equation 3.09 of Sunde, 1949) where $L$ is electrode length and $a$ is diameter. For reasonable values of $L$ and $a$, 0.1 $\Omega$ is easy to achieve, less than 0.01 $\Omega$ is harder but possible. To utilize electrodes having the lower resistance, antenna resistance must be kept comparably low, yielding wire diameters of order 2 cm. It might thus be possible to construct an antenna with a total resistance of about 0.01 $\Omega$, but much smaller would be very difficult. More likely, total antenna resistance will be between 0.1 and 1 $\Omega$. Thus with a total power of 10 kW delivered to the antenna, output currents of up to 1,000 amps are possible. With 100 kW delivered to the antenna, currents could be as large as 3,000 amps for the lowest impedance antenna. Thus, bearing in mind that 100 kW corresponds to 1,000 V and 100 A at the bottom end of a deep-tow cable, it appears that it will be hard to achieve significantly more than the 1,000 A transmission currents currently being advertised by industry, with corresponding dipole moments up to 300 kAm.

Switching such large currents entails dealing with stored energy in the transmitter antenna. The self-inductance of a long wire is given approximately by

$$Z = 0.2L[\ln(\frac{4L}{a}) - 0.75] \mu H$$

(Rosa, 1908). A typical antenna would have an inductance of order 500 microHenries. Early attempts by Charles Cox to build a transmitter failed because he ignored the effect of inductance, and the back EMF
during switching destroyed the equipment. Recognizing that voltage and current were out of phase in the antenna, he solved this problem by detecting zero current crossings in the rectifier bridge and switching at those times. In the current SIO transmitter, a capacitor bank absorbs the energy associated with the back EMF during switching.

Most current seafloor receiver instruments appear to be built around the principles outlined in Webb et al. (1985) and Constable et al. (1998), and although the modern instruments are likely to use 24 bit analog to digital conversion instead of 16 bits, and solid state data storage instead of disk drives or tape recorders, the 1 Hz noise floor of 0.1 to 1 nV/√Hz is similar. Constable and Weiss (2006) discuss the contributions to the total system noise, and with reference to Figure 2 the noise floor of current equipment is around $10^{-15} \text{V/m/(Am)}$ and unlikely to be better than $10^{-16} \text{V/m/(Am)}$ (i.e. not able to detect the reservoir layer in this example).

**Examples**

The rapid commercialization of marine CSEM and the high cost of surveys has resulted in few, if any, academically available data sets being available at this time, and most of the best quality data are proprietary. However, we are able to present examples from the first two research cruises carried out by Statoil and ExxonMobil.

![Diagram](image)

**Figure 3.** Survey layout (A) and radial mode horizontal electric field data (B) collected on receiver ‘V’ during the first proof-of-concept marine CSEM survey over a hydrocarbon reservoir (Ellingsrud et al., 2002). Water depth is 1,200 m, and the transmission frequency was 0.25 Hz. The 2D response of the reservoir was calculated using the code of Li and Key (2007, this issue).
In Figure 3, we show data from one instrument deployed towards the south edge of the reservoir during the first use of marine CSEM for hydrocarbon mapping by Statoil (Ellingsrud et al., 2002). The location is offshore Angola in about 1,000 m seawater over a known oil reservoir of considerable extent. The receivers (larger dots in Figure 3A) comprise a mixed fleet of LEMURs from Southampton University (Sinha et al., 1990), ELFs from Scripps (Webb et al., 1985), and the Scripps broadband MT/CSEM instrument of Constable et al. (1998). The transmitter was the DASI instrument of Southampton, operating at a dipole moment of 16 kAm at frequencies of 0.25 and 1 Hz.

This experiment was a huge success in that the data are clearly sensitive to the reservoir, and this alone provided the support Statoil and other companies needed to move ahead with the technique. However, the mixed fleet of receivers, along with the poor performance of the bolt-on super-short base line (SSBL) navigation system and the modest sized transmitter, resulted in a data set of highly variable quality. Furthermore, the sites in the northern part of the array, which were designed to provide off-target control, where heavily influenced by a salt body in that location. In Figure 3 we present data from one of the more modern Scripps instruments (‘Bandicoot’) which was positioned close enough to the edge of the reservoir to show an on-target and off-target response. As can be seen from the 2D modeling, simple normalization of the data by the halfspace response, as was done by Ellingsrud et al. (2002), over-estimates the extent of the reservoir since the elevated electric field response persists indefinitely off the edge of the target.

ExxonMobil were independently planning their own field trials during the Statoil survey, and surveyed three prospects offshore West Africa in early 2002 (Srnska et al., 2005). These surveys were carried out in a very similar manner to the Statoil study, using the British research vessel *RRS Charles Darwin* and the Southampton DASI transmitter. The receiver fleet, however, was now a uniform fleet of 30 modern instruments provided by Scripps, three of which were full MT/CSEM receivers, and much more effort was put into the navigation of the transmitter and receivers.

In Figure 4 we present an example from a known discovery, with data acquired in January 2002 during the three offshore West Africa surveys. Saturated middle to lower Miocene oil sands are present 1,400 m to 2,500 m below the seafloor. A total of 29 receiver positions and 210 line-kilometers of data were collected in water 1,000 m deep. The radial towing pattern maximizes the amount of in-line data collected, and has advantages for data summation and 3D inversion (Srnska and Carrazone, 2003). The transmitter, again the DASI system provided by Southampton, was towed 50 m above the seafloor at a speed of about 1.5 knots. The maximum dipole moment was 15 kAm.
Figure 4. Marine CSEM data example over a discovered field. The survey layout is shown in ‘A’, and data from receiver 21 for tow line 2 is shown in ‘B’, along with 3D forward model responses for the charged reservoir (Figure 5) and uncharged reservoir models.

Figure 5. Section through 3D resistivity model taken along tow line 2 shown in Figure 4. Background resistivity is gradational from 0.6 Ωm at the seafloor to 0.8 Ωm at depth. The resistive layers in the overburden sediments are 2–4 Ωm. Receiver positions are shown as open circles at the seafloor.

Figure 5 shows a section of the 3D resistivity model developed by iterative forward calculations guided by 3D seismic data, well log data from wells A and B, and the CSEM data collected on all instruments at all frequencies transmitted by all tow lines. The reservoir units are the four deep, highly resistive (50–70 Ωm), dipping units. Figure 4B shows source-normalized inline horizontal electric field amplitude data acquired on receiver 21 during survey tow line 2, for a frequency of 0.25 Hz (the source fundamental). The response
of the 3D forward model with all oil-filled reservoirs (solid line) and all brine-filled reservoirs (broken line) are also shown, calculated using a variant of the 3D finite difference frequency domain code of Newman and Alumbaugh (1995). It is clear that a charged reservoir model fits the data much better than a no-reservoir model.

![Figure 6](image)

**Figure 6.** Marine CSEM data collected over an active exploration prospect. Pre-drill CSEM data suggested that the potential reservoir was brine-filled, which was confirmed by drilling.

Figure 6 shows a second 2002 survey also collected offshore West Africa prior to drilling an exploration prospect in a salt withdrawal mini-basin. The survey parameters were similar to the previous example, except that fewer receivers (23) and transmitter tows (182 line-km) were used, and the water depth was deeper (1900 m). Prospective lower Miocene and Oligocene sands were located 1,200 to 1,500 m below the seafloor, with a seismic reflection signature that showed indications of hydrocarbons. In contrast to the example shown in Figures 4 and 5, here the inline horizontal electric field data fit the 3D forward model response for a brine-filled reservoir (Figure 6B). The predicted response for models of hydrocarbon filled reservoirs are significantly larger than the observed data. The CSEM prediction was thus for a dry hole, which was confirmed upon drilling. This was a success for the marine CSEM method, although less of a success from an exploration perspective. Drilling showed that the sands were partially gas saturated, which contributed to a seismic direct hydrocarbon indicator (DHI) interpretation.

Between then and the end of 2004, thirty-four additional surveys were carried out by ExxonMobil in a variety of geological environments offshore West Africa, South America, and North America in water depths between 100 m and 3,200 m. In order to evaluate the extent to which marine CSEM could be
applied to exploration problems, surveys were conducted with calibration from well control, over rank exploration prospects, and in development and production settings. It was demonstrated that marine CSEM data could be successfully acquired simultaneously with seismic surveys, drilling operations, and hydrocarbon production. From the start, ExxonMobil developed a strong 3D modeling and inversion capability, and prospect evaluation relied heavily on 3D model-based interpretation utilizing seismic depth control and geological constraints. These results have confirmed that the method is useful for distinguishing hydrocarbon reservoirs from wet sands, subject to the current limitations of the method. These limitations include signal to noise ratio, target size, and geological structure (e.g. targets below salt are largely invisible to the method as currently practiced). However, it has been shown that integrated interpretation of marine CSEM data using iterative 3D forward modeling can be effective even in complex geological settings (Green et al., 2005), and that 3D inversion can illuminate subtle resistivity effects that would otherwise be difficult to interpret manually (Carazzone et al., 2005).

Conclusions and a Look Forward

Marine CSEM may well become the most important geophysical technique to emerge since the advent of 3D reflection seismology 25 years ago. Calibrations of the method over known reservoirs, through well calibrations, and 3D model simulations demonstrates that the fundamental methodology is sound. The high quality of marine CSEM data is partly a result of the low noise environment of the deep seafloor and the good coupling of the transmitted fields to the geological structures compared to propagation through the seawater. As might be expected, interpretation is improved significantly when CSEM data are integrated with other geoscientific information such as seismic reflection data, well logs, and geological syntheses. Although the non-uniqueness of geophysical inversion and modeling, coupled with the fact that many geological formations can exhibit enhanced resistivity (evaporites, volcanics, coals, carbonates, and fresh water sands, to name a few), presents potential pitfalls to using the method, the fact that CSEM provides information that is independent from seismic velocity and intimately connected to the nature of the fluid component means that the method can make significant contributions to exploration, and possibly field development and production. Although the spatial resolution of EM methods is lower than for seismic methods, there is an intrinsic sensitivity to the depth of the target and the resolution is significantly better than for potential field methods.

The commercial development of marine CSEM has leant heavily on the academic community for software, instrumentation, and methodology, and has progressed very rapidly as a result. Further progress is going
to require the commercial sector to make advances in its own right, but so far resources have been spent mainly on transferring academic skills to industry; ‘catching up’ if you like. For example, data quality as characterized by transmitter–receiver system noise floor has improved by only a little more than an order of magnitude from the worst of the academic data (a little more than $10^{-14}$ V/(Am$^2$)) to the best of the current commercial data (a little less than $10^{-15}$ V/(Am$^2$)), mainly through a brute-force increase in source dipole moment. The only significant modification to the original marine CSEM method as proposed 25 years ago is the collection of vertical electric field data. The most likely near-term innovations are the collection of a much broader frequency spectrum of data along with more numerous receiver instruments, and the continuous collection of data in a reconnaissance survey mode.

Current efforts have focussed on screening previously identified prospects. Once the methods have been adopted by industry, and the equipment made commercially available, one can envisage a variety of other applications. Time-lapse methods for reservoir monitoring during production (so-called 4D-EM) are an obvious application of the technology, possibly incorporating borehole transmitters or receivers, and certainly improving the repeat survey method by installation of fixed infrastructure. Use of higher frequencies and shorter offsets will allow resistivity structure in the shallow section to be studied, useful for avoiding drilling hazards such as gas hydrates (e.g. Weitemeyer et al., 2006). The seismic method has dominated exploration so effectively that it is possible that the discovery of reservoirs is biased towards those with a seismic signature, and as we gain confidence and expertise in marine CSEM methods we may be able to explore for hydrocarbons that are visible only through their resistivity signature. Indeed, the optimists among us may imagine that marine CSEM will play a critical role in providing the necessary supply of hydrocarbons for the world’s growing economy, and thus help ease the eventual transition to other energy sources.

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